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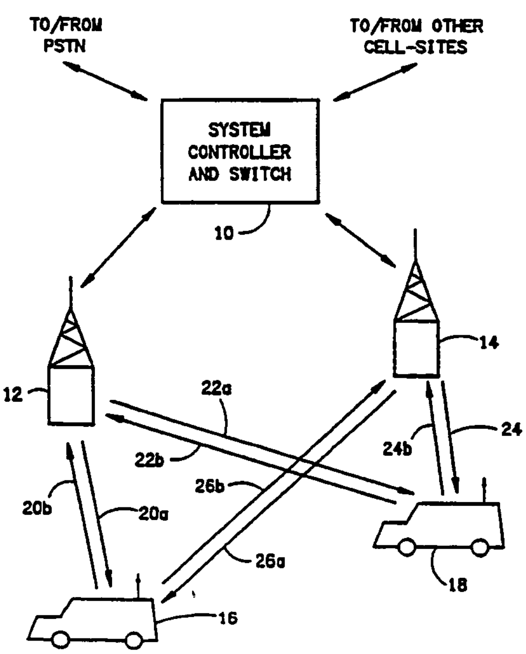
(54) Title: SYSTEM AND METHOD FOR GENERATING SIGNAL WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM

(57) Abstract

A system and method for communicating information signals using spread spectrum communication techniques. PN sequences are constructed that provide orthogonality between the users so that mutual interference will be reduced, allowing higher capacity and better link performance. With orthogonal PN codes, the cross-correlation is zero over a predetermined time interval, resulting in no interference between the orthogonal codes, provided only that the code time frames are time aligned with each other. In an exemplary embodiment, signals are communicated between a cell-site (12, 14) and mobile units (16, 18) using direct sequence spread spectrum communication signals. In the cell-to-mobile link, pilot, sync, paging and voice channels are defined. Information communicated on the cell-to-mobile link channels are, in general, encoded, interleaved, bi-phase shift key (BPSK) modulated with orthogonal covering of each BPSK symbol along with quadrature phase shift key (QPSK) spreading of the covered symbols. In the mobile-to-cell link, access and voice channels are defined. Information communicated on the mobile-to-cell link channels are, in general, encoded, interleaved, orthogonal signalling along with QPSK spreading.



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SYSTEM AND METHOD FOR GENERATING SIGNAL WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to cellular telephone systems. More specifically, the present invention relates to a novel and improved system and method for communicating information, in a mobile cellular telephone system or satellite mobile telephone system, using spread spectrum communication signals.

II. Description of the Related Art

The use of code division multiple access (CDMA) modulation techniques is one of several techniques for facilitating communications in which a large number of system users are present. Other multiple access communication system techniques, such as time division multiple access (TDMA), frequency division multiple access (FDMA) and AM modulation schemes such as amplitude companded single sideband (ACSSB) are known in the art. However the spread spectrum modulation technique of CDMA has significant advantages over these modulation techniques for multiple access communication systems. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Patent No. 4,901,307, issued February 13, 1990, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS", assigned to the assignee of the present invention, of which the disclosure thereof is incorporated by reference.

In the just mentioned patent, a multiple access technique is disclosed where a large number of mobile telephone system users each

having a transceiver communicate through satellite repeaters or terrestrial base stations (also referred to as cell-sites stations, cell-sites or for short, cells) using code division multiple access (CDMA) spread spectrum communication signals. In using CDMA communications, the frequency spectrum can be reused multiple times thus permitting an increase in system user capacity. The use of CDMA results in a much higher spectral efficiency than can be achieved using other multiple access techniques.

The satellite channel typically experiences fading that is characterized as Rician. Accordingly the received signal consists of a direct component summed with a multiple reflected component having Rayleigh fading statistics. The power ratio between the direct and reflected component is typically on the order of 6-10 dB, depending upon the characteristics of the mobile unit antenna and the environment about the mobile unit.

Contrasting with the satellite channel, the terrestrial channel experiences signal fading that typically consists of the Rayleigh faded component without a direct component. Thus, the terrestrial channel presents a more severe fading environment than the satellite channel in which Rician fading is the dominant fading characteristic.

The Rayleigh fading characteristic in the terrestrial channel signal is caused by the signal being reflected from many different features of the physical environment. As a result, a signal arrives at a mobile unit receiver from many directions with different transmission delays. At the UHF frequency bands usually employed for mobile radio communications, including those of cellular mobile telephone systems, significant phase differences in signals traveling on different paths may occur. The possibility for destructive summation of the signals may result, with on occasion deep fades occurring.

Terrestrial channel fading is a very strong function of the physical position of the mobile unit. A small change in position of the mobile unit changes the physical delays of all the signal propagation paths, which further results in a different phase for each path. Thus, the

motion of the mobile unit through the environment can result in a quite rapid fading process. For example, in the 850 MHz cellular radio frequency band, this fading can typically be as fast as one fade per second per mile per hour of vehicle speed. Fading this severe can be extremely disruptive to signals in the terrestrial channel resulting in poor communication quality. Additional transmitter power can be used to overcome the problem of fading. However, such power increases effect both the user, in excessive power consumption, and the system by increased interference.

The CDMA modulation techniques disclosed in U.S. Patent No. 4,901,307 offer many advantages over narrow band modulation techniques used in communication systems employing satellite or terrestrial repeaters. The terrestrial channel poses special problems to any communication system particularly with respect to multipath signals. The use of CDMA techniques permit the special problems of the terrestrial channel to be overcome by mitigating the adverse effect of multipath, e.g. fading, while also exploiting the advantages thereof.

In a CDMA cellular telephone system, the same frequency band can be used for communication in all cells. The CDMA waveform properties that provide processing gain are also used to discriminate between signals that occupy the same frequency band. Furthermore the high speed pseudonoise (PN) modulation allows many different propagation paths to be separated, provided the difference in path delays exceed the PN chip duration, i.e. 1/bandwidth. If a PN chip rate of approximately 1 MHz is employed in a CDMA system, the full spread spectrum processing gain, equal to the ratio of the spread bandwidth to system data rate, can be employed against paths that differ by more than one microsecond in path delay from the desired path. A one microsecond path delay differential corresponds to differential path distance of approximately 1,000 feet. The urban environment typically provides differential path delays in excess of one microsecond, and up to 10-20 microseconds are reported in some areas.

In narrow band modulation systems such as the analog FM modulation employed by conventional telephone systems, the existence of multiple paths results in severe multipath fading. With wide band CDMA modulation, however, the different paths may be discriminated against in the demodulation process. This discrimination greatly reduces the severity of multipath fading. Multipath fading is not totally eliminated in using CDMA discrimination techniques because there will occasionally exist paths with delayed differentials of less than the PN chip duration for the particular system. Signals having path delays on this order cannot be discriminated against in the demodulator, resulting in some degree of fading.

It is therefore desirable that some form of diversity be provided which would permit a system to reduce fading. Diversity is one approach for mitigating the deleterious effects of fading. Three major types of diversity exist: time diversity, frequency diversity and space diversity.

Time diversity can best be obtained by the use of repetition, time interleaving, and error detection and coding which is a form of repetition. The present invention employs each of these techniques as a form of time diversity.

CDMA by its inherent nature of being a wideband signal offers a form of frequency diversity by spreading the signal energy over a wide bandwidth. Therefore, frequency selective fading affects only a small part of the CDMA signal bandwidth.

Space or path diversity is obtained by providing multiple signal paths through simultaneous links from a mobile user through two or more cell-sites. Furthermore, path diversity may be obtained by exploiting the multipath environment through spread spectrum processing by allowing a signal arriving with different propagation delays to be received and processed separately. Examples of path diversity are illustrated in copending U.S. Patent Application entitled "SOFT HANDOFF IN A CDMA CELLULAR TELEPHONE SYSTEM", Serial No. 07/433,030, filed November 7, 1989, and copending U.S. Patent

Application entitled "DIVERSITY RECEIVER IN A CDMA CELLULAR TELEPHONE SYSTEM", Serial No. 07/432,552, also filed November 7, 1989, both assigned to the assignee of the present invention.

The deleterious effects of fading can be further controlled to a certain extent in a CDMA system by controlling transmitter power. A system for cell-site and mobile unit power control is disclosed in copending U.S. Patent Application entitled "METHOD AND APPARATUS FOR CONTROLLING TRANSMISSION POWER IN A CDMA CELLULAR MOBILE TELEPHONE SYSTEM", Serial No. 07/433,031, filed November 7, 1989, also assigned to the assignee of the present invention.

The CDMA techniques as disclosed in U.S. Patent No. 4,901,307 contemplated the use of coherent modulation and demodulation for both directions of the link in mobile-satellite communications. Accordingly, disclosed therein is the use of a pilot carrier signal as a coherent phase reference for the satellite-to-mobile link and the cell-to-mobile link. In the terrestrial cellular environment, however, the severity of multipath fading, with the resulting phase disruption of the channel, precludes usage of coherent demodulation technique for the mobile-to-cell link. The present invention provides a means for overcoming the adverse effects of multipath in the mobile-to-cell link by using noncoherent modulation and demodulation techniques.

The CDMA techniques as disclosed in U.S. Patent No. 4,901,307 further contemplated the use of relatively long PN sequences with each user channel being assigned a different PN sequence. The cross-correlation between different PN sequences and the autocorrelation of a PN sequence for all time shifts other than zero both have a zero average value which allows the different user signals to be discriminated upon reception

However, such PN signals are not orthogonal. Although the cross-correlations average to zero, for a short time interval such as an information bit time the cross-correlation follows a binomial distribution. As such, the signals interfere with each other much the

same as if they were wide bandwidth Gaussian noise at the same power spectral density. Thus the other user signals, or mutual interference noise, ultimately limits the achievable capacity.

The existence of multipath can provide path diversity to a wideband PN CDMA system. If two or more paths are available with greater than one microsecond differential path delay, two or more PN receivers can be employed to separately receive these signals. Since these signals will typically exhibit independence in multipath fading, i.e., they usually do not fade together, the outputs of the two receivers can be diversity combined. Therefore a loss in performance only occurs when both receivers experience fades at the same time. Hence, one aspect of the present invention is the provision of two or more PN receivers in combination with a diversity combiner. In order to exploit the existence of multipath signals, to overcome fading, it is necessary to utilize a waveform that permits path diversity combining operations to be performed.

It is therefore an object of the present invention to provide for the generation of PN sequences which are orthogonal so as to reduce mutual interference, thereby permitting greater user capacity, and support path diversity thereby overcoming fading.

SUMMARY OF THE INVENTION

The implementation of spread spectrum communication techniques, particularly CDMA techniques, in the mobile cellular telephone environment therefore provides features which vastly enhance system reliability and capacity over other communication system techniques. CDMA techniques as previously mentioned further enable problems such as fading and interference to be readily overcome. Accordingly, CDMA techniques further promote greater frequency reuse, thus enabling a substantial increase in the number of system users.

The present invention is a novel and improved method and system for constructing PN sequences that provide orthogonality between the users so that mutual interference will be reduced, allowing higher capacity and better link performance. With orthogonal PN codes, the cross-correlation is zero over a predetermined time interval, resulting in no interference between the orthogonal codes, provided only that the code time frames are time aligned with each other.

In an exemplary embodiment, signals are communicated between a cell-site and mobile units using direct sequence spread spectrum communication signals. In the cell-to-mobile link, pilot, sync, paging and voice channels are defined. Information communicated on the cell-to-mobile link channels are, in general, encoded, interleaved, bi-phase shift key (BPSK) modulated with orthogonal covering of each BPSK symbol along with quadrature phase shift key (QPSK) spreading of the covered symbols.

In the mobile-to-cell link, access and voice channels are defined. Information communicated on the mobile-to-cell link channels are, in general, encoded, interleaved, orthogonal signalling along with QPSK spreading.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, objects, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

Figure 1 is a schematic overview of an exemplary CDMA cellular telephone system;

Figure 2 is a block diagram of the cell-site equipment as implemented in the CDMA cellular telephone system;

Figure 3 is a block diagram of the cell-site receiver;

Figure 4 is a block diagram of the cell-site transmit modulator; and

Figure 5 is an exemplary timing diagram of sync channel symbol synchronization;

Figure 6 is an exemplary timing diagram of sync channel timing with orthogonal covering;

Figure 7 is an exemplary timing diagram of the overall cell-to-mobile link timing;

Figure 8 is a block diagram of the mobile telephone switching office equipment;

Figure 9 is a block diagram of the mobile unit telephone configured for CDMA communications in the CDMA cellular telephone system;

Figure 10 is a block diagram of the mobile unit receiver; and

Figure 11 is a block diagram of the mobile unit transmit modulator;

Figure 12 is an exemplary timing diagram of the mobile-to-cell link for the variable data rate with burst transmission; and

Figure 13 is an exemplary timing diagram of the overall mobile-to-cell link timing.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In a CDMA cellular telephone system, each cell-site has a plurality of modulator-demodulator units or spread spectrum modems. Each modem consists of a digital spread spectrum transmit modulator, at least one digital spread spectrum data receiver and a searcher receiver. Each modem at the cell-site is assigned to a mobile unit as needed to facilitate communications with the assigned mobile unit.

A soft handoff scheme is employed for a CDMA cellular telephone system in which a new cell-site modem is assigned to a mobile unit while the old cell-site modem continues to service the call. When the mobile unit is located in the transition region between the two cell-sites,

the call can be switched back and forth between cell-sites as signal strength dictates. Since the mobile unit is always communicating through at least one cell-site modem, fewer disrupting effects to the mobile unit or in service will occur. The mobile unit thus utilizes multiple receivers for assisting in the handoff process in addition to a diversity function for mitigating the effects of fading.

In the CDMA cellular telephone system, each cell-site transmits a "pilot carrier" signal. Should the cell be divided into sectors, each sector has an associated distinct pilot signal within the cell. This pilot signal is used by the mobile units to obtain initial system synchronization and to provide robust time, frequency and phase tracking of the cell-site transmitted signals. Each cell-site also transmits spread spectrum modulated information, such as cell-site identification, system timing, mobile paging information and various other control signals.

The pilot signal transmitted by each sector of each cell is of the same spreading code but with a different code phase offset. Phase offset allows the pilot signals to be distinguished from one another thus distinguishing originating cell-sites or sectors. Use of the same pilot signal code allows the mobile unit to find system timing synchronization by a single search through all pilot signal code phases. The strongest pilot signal, as determined by a correlation process for each code phase, is readily identifiable. The identified strongest pilot signal generally corresponds to the pilot signal transmitted by the nearest cell-site. However, the strongest pilot signal is used whether or not it is transmitted by the closest cell-site.

Upon acquisition of the strongest pilot signal, i.e. initial synchronization of the mobile unit with the strongest pilot signal, the mobile unit searches for another carrier intended to be received by all system users in the cell. This carrier, called the synchronization channel, transmits a broadcast message containing system information for use by the mobiles in the system. The system information identifies the cell-site and the system in addition to conveying information which allows the long PN codes, interleaver frames, vocoders and other system timing

information used by the mobile mobile unit to be synchronized without additional searching. Another channel, called the paging channel may also be provided to transmit messages to mobiles indicating that a call has arrived for them, and to respond with channel assignments when a mobile initiates a call.

The mobile unit continues to scan the received pilot carrier signal code at the code offsets corresponding to cell-site neighboring sector or neighboring transmitted pilot signals. This scanning is done in order to determine if a pilot signal emanating from a neighboring sector or cell is becoming stronger than the pilot signal first determined to be strongest. If, while in this call inactive mode, a neighbor sector or neighbor cell-site pilot signal becomes stronger than that of the initial cell-site sector or cell-site transmitted pilot signal, the mobile unit will acquire the stronger pilot signals and corresponding sync and paging channel of the new sector or cell-site.

When a call is initiated, a pseudonoise (PN) code address is determined for use during the course of this call. The code address may be either assigned by the cell-site or be determined by prearrangement based upon the identity of the mobile unit. After a call is initiated the mobile unit continues to scan the pilot signal transmitted by the cell-site through which communications are established in addition to pilot signal of neighboring sectors or cells. Pilot signal scanning continues in order to determine if one of the neighboring sector or cell transmitted pilot signals becomes stronger than the pilot signal transmitted by the cell-site the mobile unit is in communication with. When the pilot signal associated with a neighboring cell or cell sector becomes stronger than the pilot signal of the current cell or cell sector, it is an indication to the mobile unit that a new cell or cell sector has been entered and that a handoff should be initiated.

An exemplary telephone system in which the present invention is embodied is illustrated in Figure 1. The system illustrated in Figure 1 utilizes spread spectrum modulation techniques in communication between the system mobile units or mobile telephones, and the cell-sites.

Cellular systems in large cities may have hundreds of cell-site stations serving hundreds of thousands of mobile telephones. The use of spread spectrum techniques, in particular CDMA, readily facilitates increases in user capacity in systems of this size as compared to conventional FM modulation cellular systems.

In Figure 1, system controller and switch 10, also referred to as mobile telephone switching office (MTSO), typically includes interface and processing circuitry for providing system control to the cell-sites. Controller 10 also controls the routing of telephone calls from the public switched telephone network (PSTN) to the appropriate cell-site for transmission to the appropriate mobile unit. Controller 10 also controls the routing of calls from the mobile units, via at least one cell-site, to the PSTN. Controller 10 may connect calls between mobile users via the appropriate cell-sites since the mobile units do not typically communicate directly with one another.

Controller 10 may be coupled to the cell-sites by various means such as dedicated telephone lines, optical fiber links or microwave communication links. In Figure 1, two such exemplary cell-sites 12 and 14 including, along with mobile units 16 and 18 each including a cellular telephone are illustrated. Cell-sites 12 and 14 as discussed herein and illustrated in the drawings are considered to service an entire cell. However it should be understood that the cell may be geographically divided into sectors with each sector treated as a different coverage area. Accordingly, handoffs are made between sectors of a same cell as is described herein for multiple cells, while diversity may also be achieved between sectors as is for cells.

In Figure 1, arrowed lines 20a-20b and 22a-22b respectively define the possible communication links between cell-site 12 and mobile unit 16 and 18. Similarly, arrowed lines 24a-24b and 26a-26b respectively define the possible communication links between cell-site 14 and mobile units 16 and 18. Cell-sites 12 and 14 nominally transmit using equal power.

The cell-site service areas or cells are designed in geographic shapes such that the mobile unit will normally be closest to one cell-site, and within one cell sector should the cell be divided into sectors. When the mobile unit is idle, i.e. no calls in progress, the mobile unit constantly monitors the pilot signal transmissions from each nearby cell-site, and if applicable from a single cell-site in which the cell is sectorized. As illustrated in Figure 1, the pilot signals are respectively transmitted to mobile unit 16 by cell-sites 12 and 14 upon outbound or forward communication links 20a and 26a. Mobile unit 16 can determine which cell it is in by comparing signal strength in pilot signals transmitted from cell-sites 12 and 14.

In the example illustrated in Figure 1, mobile unit 16 may be considered closest to cell-site 12. When mobile unit 16 initiates a call, a control message is transmitted to the nearest cell-site, cell-site 12. Cell-site 12 upon receiving the call request message, transfers the called number to system controller 10. System controller 10 then connects the call through the PSTN to the intended recipient.

Should a call be initiated within the PSTN, controller 10 transmits the call information to all the cell-sites in the area. The cell-sites in return transmit a paging message within each respective coverage area that is intended for the called recipient mobile user. When the intended recipient mobile unit hears the page message, it responds with a control message that is transmitted to the nearest cell-site. This control message signals the system controller that this particular cell-site is in communication with the mobile unit. Controller 10 then routes the call through this cell-site to the mobile unit. Should mobile unit 16 move out of the coverage area of the initial cell-site, cell-site 12, an attempt is made to continue the call by routing the call through another cell-site.

With respect to cellular telephone systems, The Federal Communications Commission (FCC) has allocated a total of 25 MHz for mobile-to-cell links and 25 MHz for cell-to-mobile links. The FCC has divided the allocation equally between two service providers, one of which is the wireline telephone company for the service area and the

other chosen by lottery. Because of the order in which allocations were made, the 12.5 MHz allocated to each carrier for each direction of the link is further subdivided into two sub-bands. For the wireline carriers, the sub-bands are each 10 MHz and 2.5 MHz wide. For the non-wireline carriers, the sub-bands are each 11 MHz and 1.5 MHz wide. Thus, a signal bandwidth of less than 1.5 MHz could be fit into any of the sub-bands, while a bandwidth of less than 2.5 MHz could be fit into all but one sub-band.

To preserve maximum flexibility in allocating the CDMA technique to the available cellular frequency spectrum, the waveform utilized in the cellular telephone system should be less than 1.5 MHz in bandwidth. A good second choice would be a bandwidth of about 2.5 MHz, allowing full flexibility to the wireline cellular carriers and nearly full flexibility to non-wireline cellular carriers. While using a wider bandwidth has the advantage of offering increased multipath discrimination, disadvantages exist in the form of higher equipment costs and lower flexibility in frequency assignment within the allocated bandwidth.

In a spread spectrum cellular telephone system, such as illustrated in Figure 1, the preferred waveform design implemented involves a direct sequence pseudonoise spread spectrum carrier. The chip rate of the PN sequence is chosen to be 1.2288 MHz in the preferred embodiment. This particular chip rate is chosen so that the resulting bandwidth, about 1.25 MHz after filtering, is approximately one-tenth of the total bandwidth allocated to one cellular service carrier.

Another consideration in the choice of the exact chip rate is that it is desirable that the chip rate be exactly divisible by the baseband data rates to be used in the system. It is also desirable for the divisor to be a power of two. In the preferred embodiment, the baseband data rate is 9600 bits per second, leading to a choice of 1.2288 MHz, 128 times 9600 for the PN chip rate.

In the cell-to-mobile link, the binary sequences used for spreading the spectrum are constructed from two different types of sequences, each

with different properties to provide different functions. There is an outer code that is shared by all signals in a cell or sector that is used to discriminate between multipath signals. The outer code is also used to discriminate between signals transmitted by different cells or sectors to the mobile units. There is also an inner code that is used to discriminate between user signals transmitted by single sector or cell.

The carrier waveform design in the preferred embodiment for the cell-site transmitted signals utilizes a sinusoidal carrier that is quadraphase (four phase) modulated by a pair of binary PN sequences that provide the outer code transmitted by a single sector or cell. The sequences are generated by two different PN generators of the same sequence length. One sequence bi-phase modulates the in-phase channel (I Channel) of the carrier and the other sequence bi-phase modulates the quadrature phase (Q Channel) of the carrier. The resulting signals are summed to form a composite four-phase carrier.

Although the values of a logical "zero" and a logical "one" are conventionally used to represent the binary sequences, the signal voltages used in the modulation process are +V volts for a logical "one" and -V volts for a logical "zero". To bi-phase modulate a sinusoidal signal, a zero volt average value sinusoid is multiplied by the +V or -V voltage level as controlled by the binary sequences using a multiplier circuit. The resulting signal may then be band limited by passing through a bandpass filter. It is also known in the art to lowpass filter the binary sequence stream prior to multiplying by the sinusoidal signal, thereby interchanging the order of the operations. A quadraphase modulator consists of two bi-phase modulators each driven by a different sequence and with the sinusoidal signals used in the bi-phase modulators having a 90° phase shift therebetween.

In the preferred embodiment, the sequence length for the transmitted signal carrier is chosen to be 32768 chips. Sequences of this length can be generated by a modified maximal length linear sequence generator by adding a zero bit to a length 32767 chip sequence. The resulting sequence has good cross-correlation and autocorrelation